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16. Abstract

The dynamic stability of the flap/lag/torsion motion of a uniform, cantilever rotor blade in hover is calculated. The influence of blade collective pitch, lag frequency, torsional flexibility, structural coupling, and precone angle on the stability is examined. Good agreement is found with the results of an independent analytical investigation.

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SUMMARY

The dynamic stability of the flap/lag/torsion motion of a uniform, cantilever rotor blade in hover is calculated. The influence of blade collective pitch, lag frequency, torsional flexibility, structural coupling, and precone angle on the stability is examined. Good agreement is found with the results of an independent analytical investigation.

INTRODUCTION

A comprehensive aeroelastic analysis for rotorcraft was developed in reference 1. This report presents the results of an application of that analysis to the case of a uniform, cantilever rotor blade in hover. A similar investigation of hingeless rotor flap/lag/torsion dynamics is given in reference 2. The purpose of the present investigation is to verify that these two independent analyses are consistent representations of the physical behavior of a rotor blade.

ANALYTICAL MODEL

The case considered is a single, independent rotor blade in hover. The blade has cantilever root restraint with uniform inertial and structural properties. The blade is assumed to have no twist; no hub offset, droop, or sweep; no kinematic pitch/bending coupling; no lag damper or structural

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damping; and no chordwise offset of the center of gravity, aerodynamic center, or tension center from the elastic axis. The influence of precone is investigated for some cases. The aerodynamic model for this investigation neglects the effects of compressibility, stall, tip loss, and root cutout. Uniform ideal induced velocity is used, calculated from momentum theory for the thrust of the single blade. See reference 1 for a detailed description of the manner in which these parameters are incorporated in the analysis.

It is assumed that the rotor blade has a Lock number $\gamma = 5$ (based on the characteristic inertia $I_b = mR^3/3$, where m is the section mass and R the blade radius). The blade chord-to-radius ratio is $c/R = 0.07854$, corresponding to a solidity of $\sigma = 0.025$ for this single blade. The blade torsional radius of gyration is $k_\theta = (I_\theta/m)^{\frac{1}{2}} = 0.025R$. The blade section aerodynamics are defined by the lift curve slope $c_{\ell_\alpha} = 5.7$, and the profile drag coefficient $c_d = 0.009$. The static pitch moment about the aerodynamic center is zero, $c_{m_{ac}} = 0$.

The blade bending and torsional stiffnesses are adjusted to achieve the desired natural frequencies. The rotating natural frequency of the flap motion is $\nu_\beta = 1.15$ (per rev) for all cases. The rotating natural frequency of the lag motion is a major parameter of the investigation, with special attention to the cases $\nu_\zeta = 0.7$ and $\nu_\zeta = 1.5$ (typical soft-inplane and stiff-inplane rotors). The blade structural coupling is defined by the parameter R, such that when the blade aerodynamic pitch is θ, the pitch of the structural principal axes is $R\theta$. For $R = 0$ there is no structural coupling, so the blade bending modes are purely inplane or purely out-of-plane. For $R = 1$ there is full structural coupling of the flap and lag bending motion. The case of infinite torsional stiffness is examined, as well as the case of a torsionally flexible blade. The torsional natural frequency is ω_ϕ (per rev).

The analysis considers three degrees of freedom: the fundamental flap, lag, and torsion modes. Infinite control system stiffness is assumed, so there is no rigid pitch motion of the blade about the pitch bearing. For the case of infinite blade torsional stiffness the problem reduces to two degrees of freedom, flap and lag bending.

RESULTS AND DISCUSSION

Figures 1 to 3 show the trim conditions calculated for this rotor blade in hover: the thrust coefficient to solidity ratio, the coning angle, and the lag angle as a function of blade collective pitch. The very high values of C_T/σ are possible because stall has been neglected. The lag deflection is determined by the balance of the relatively small inplane forces, hence is more sensitive to the structural coupling than is the trim coning angle. Figure 4 gives the blade bending frequencies as a function of the structural pitch angle, for a soft-inplane blade ($\nu_\zeta = 0.7$ at $R\theta = 0$) and a stiff-inplane blade ($\nu_\zeta = 1.5$ at $R\theta = 0$). Figure 5 shows the corresponding tip deflections of the flap and lag modes. The soft-inplane rotor has relatively close flap and lag bending stiffnesses, and so exhibits little coupling of the inplane and out-of-plane motions as $R\theta$ increases.

Figures 6 and 7 present the calculated dynamic stability of a torsionally rigid blade. For certain combinations of lag frequency and structural coupling, a flap/lag instability is encountered if the blade pitch is high enough. The stability boundary is given in terms of the critical collective pitch angle, θ_{crit}. The stiff-inplane rotors are much more sensitive to the structural coupling than are the soft-inplane rotors.

Figure 8 presents the calculated stability boundaries for a blade with torsional natural frequency $\omega_\phi = 5$. Comparing with figure 7, it is seen that torsional flexibility is generally destabilizing for small structural coupling, but stabilizing for large structural coupling. Figures 9 and 10 show the influence of precone angle β_p on the calculated stability boundaries, for soft-inplane and stiff-inplane torsionally flexible blades. Finally, figure 11 gives the lag mode damping ratio as a function of lag frequency and structural coupling, for $\omega_\phi = 5$.

A similar, but completely independent analysis of rotor blade flap/lag/torsion dynamic stability is given in reference 2. In that work an analysis limited to a single uniform, cantilever blade is used in an extensive investigation of the fundamental dynamic characteristics of hingeless rotors. There is good agreement between the present calculations and those of reference 2 (compare the present figures 6 to 11 with respectively figures 19, 22, 29, 34, 36, and 42 of reference 2). There are some numerical differences between the two calculations. For example, in figure 7 the stability boundary minimum is at about $\theta_{crit} = 9^{\circ}$, while figure 22 of reference 2 gives about $\theta_{crit} = 12^{\circ}$, a difference probably attributable to the use here of the induced velocity of a single-bladed rotor rather than a four-bladed rotor as in reference 2. In general character the results of these two independent analyses are identical, indicating that they are consistent representations of the physical behavior of a rotor blade.

CONCLUSION

The flap/lag/torsion stability of a uniform, cantilever rotor blade in hover has been examined. Good agreement was found with the results of an independent analytical investigation. Thus applications of the aeroelastic analysis developed in reference 1 to general rotors and rotorcraft configurations are supported by the basic studies of blade flap/lag/torsion dynamics in reference 2.

REFERENCES

1 Johnson, Wayne, "Aeroelastic Analysis for Rotorcraft in Flight or in a Wind Tunnel," NASA TN D-8515, 1977.

2 Hodges, Dewey H., and Ormiston, Robert A., "Stability of Elastic Bending and Torsion of Uniform Cantilever Rotor Blades in Hover with Variable Structural Coupling," NASA TN D-8192, April 1976

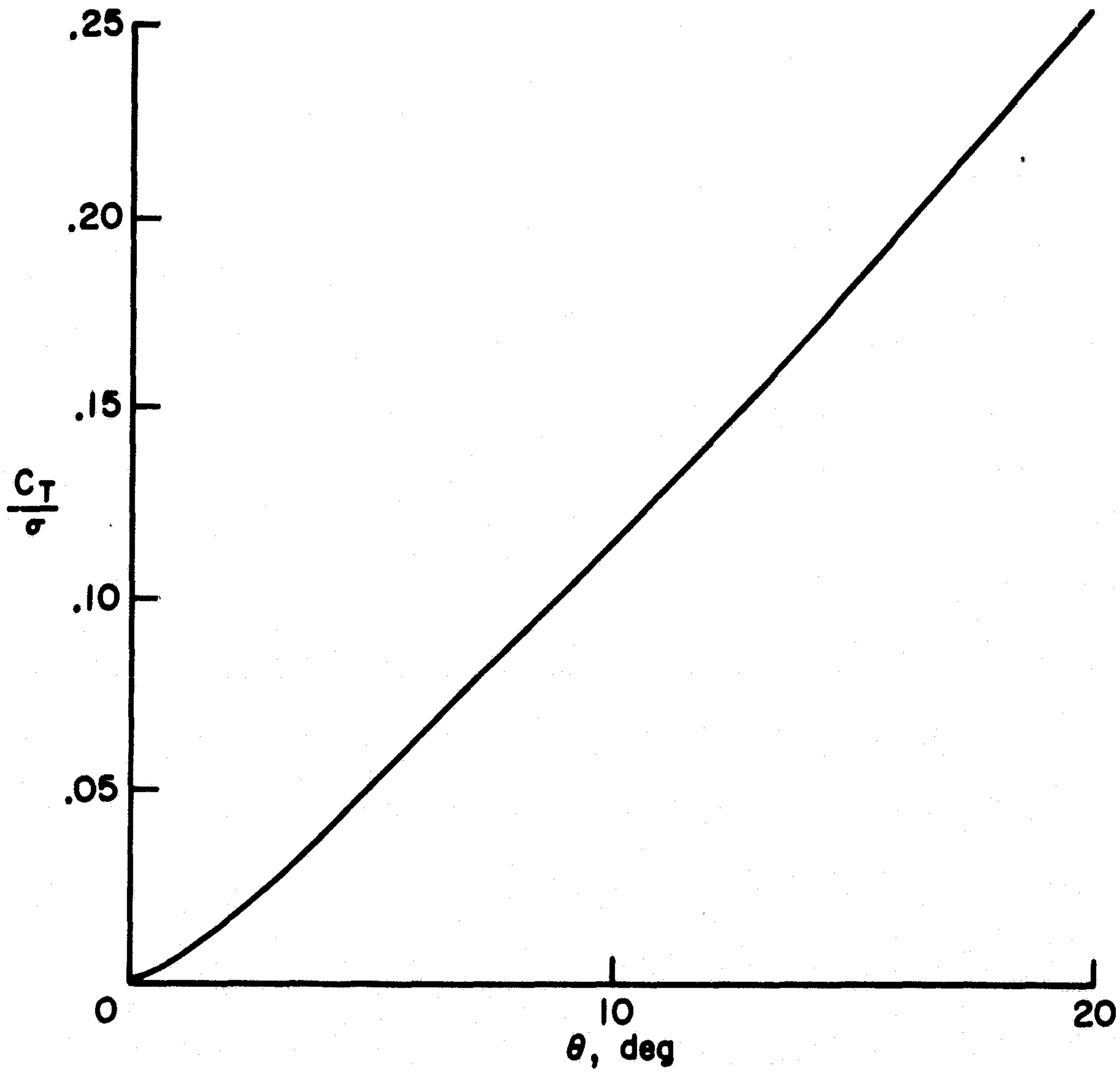


Figure 1 Thrust coefficient to solidity ratio as a function of blade collective pitch angle.

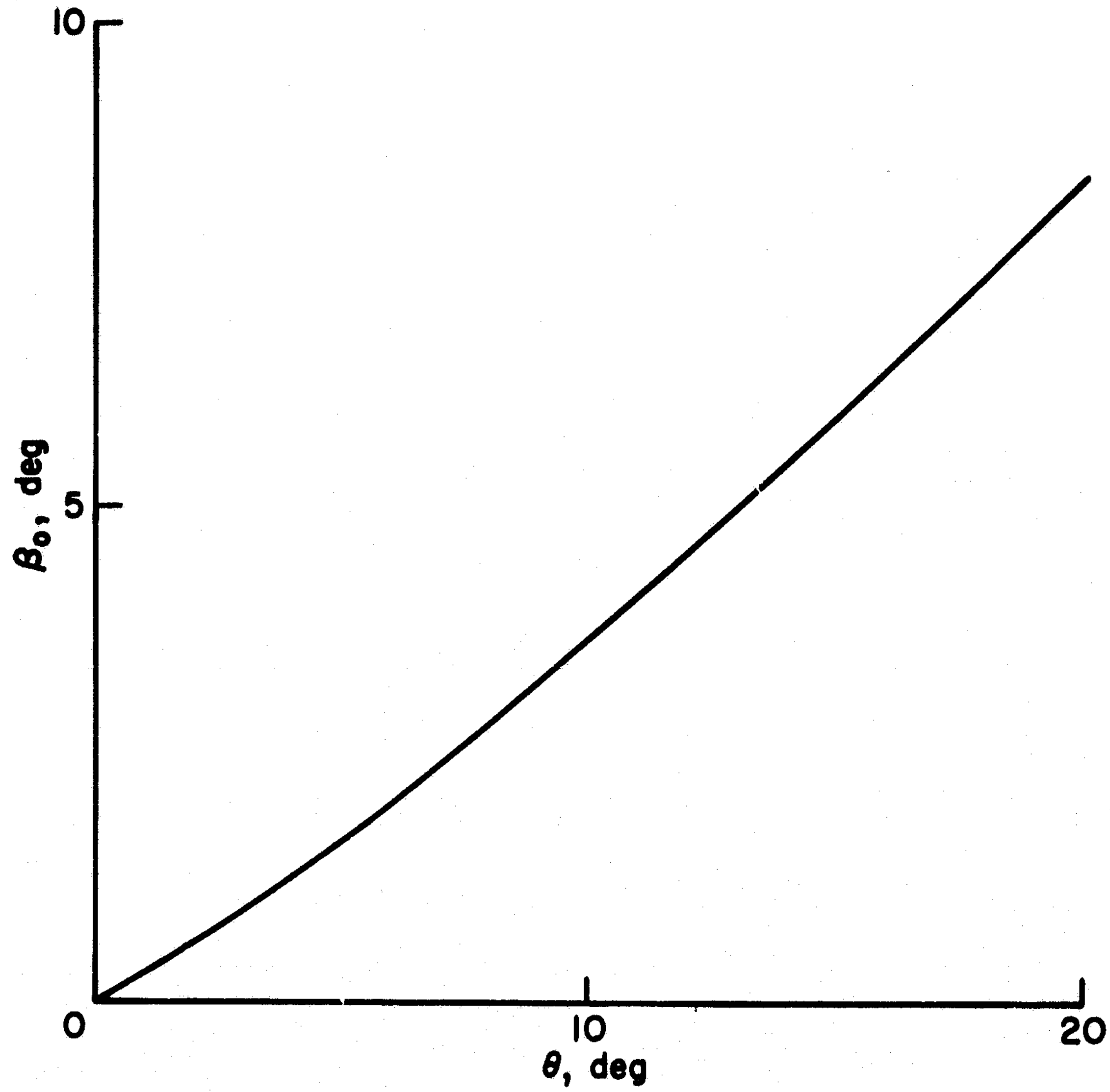


Figure 2 Trim coning angle as a function of blade collective pitch angle.

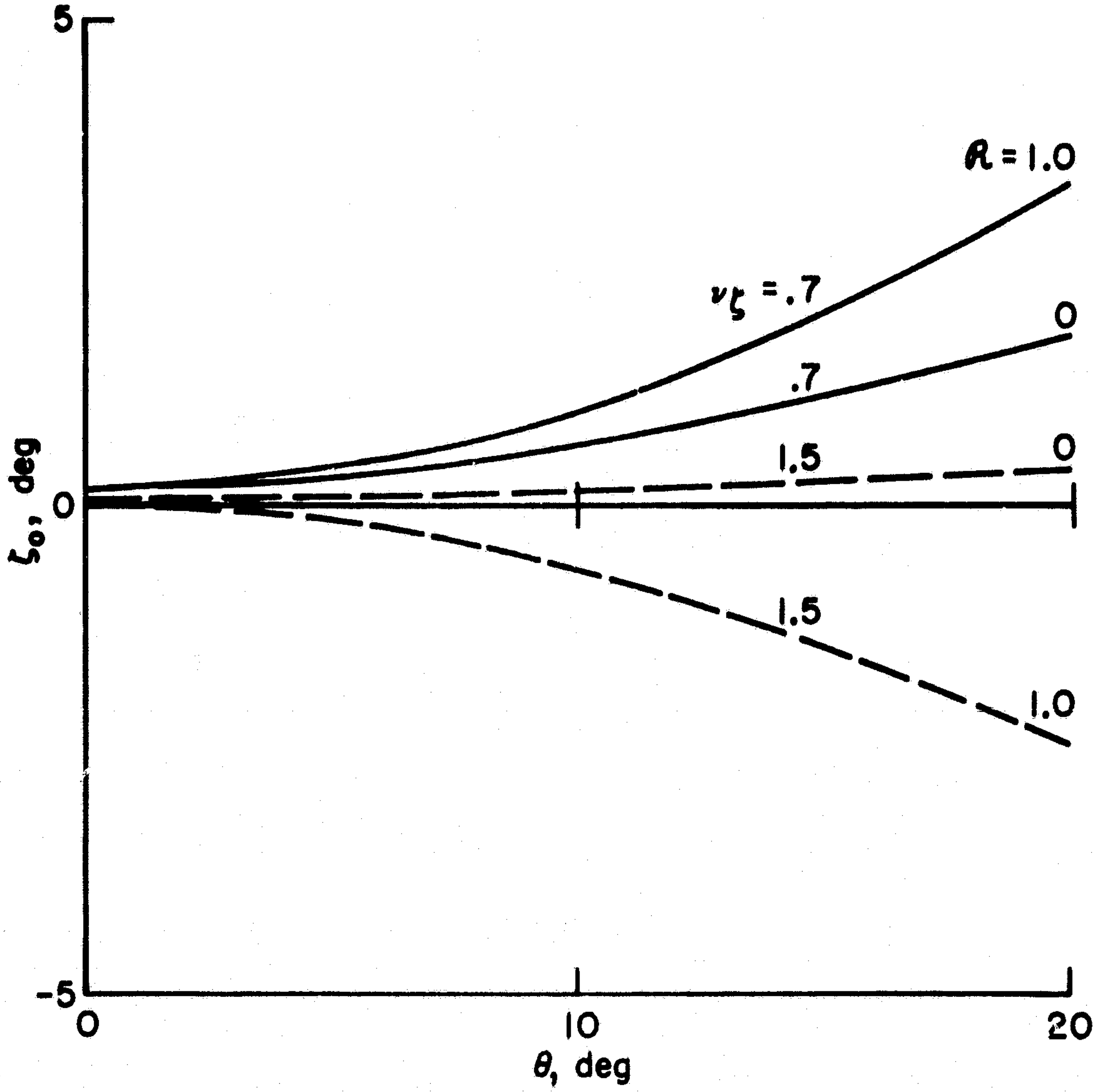


Figure 3 Trim lag angle as a function of blade collective pitch angle, for various values of lag frequency and structural coupling.

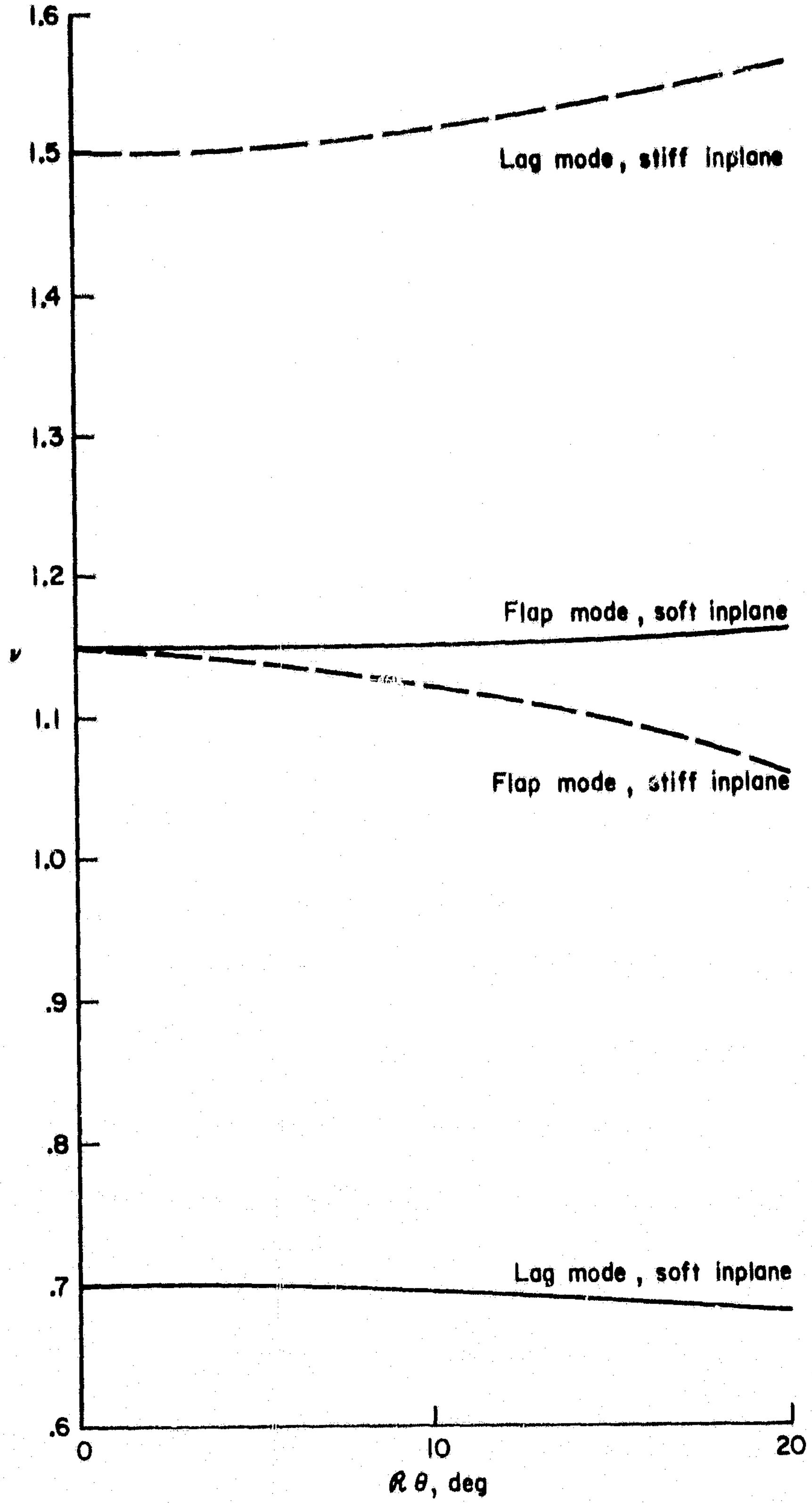
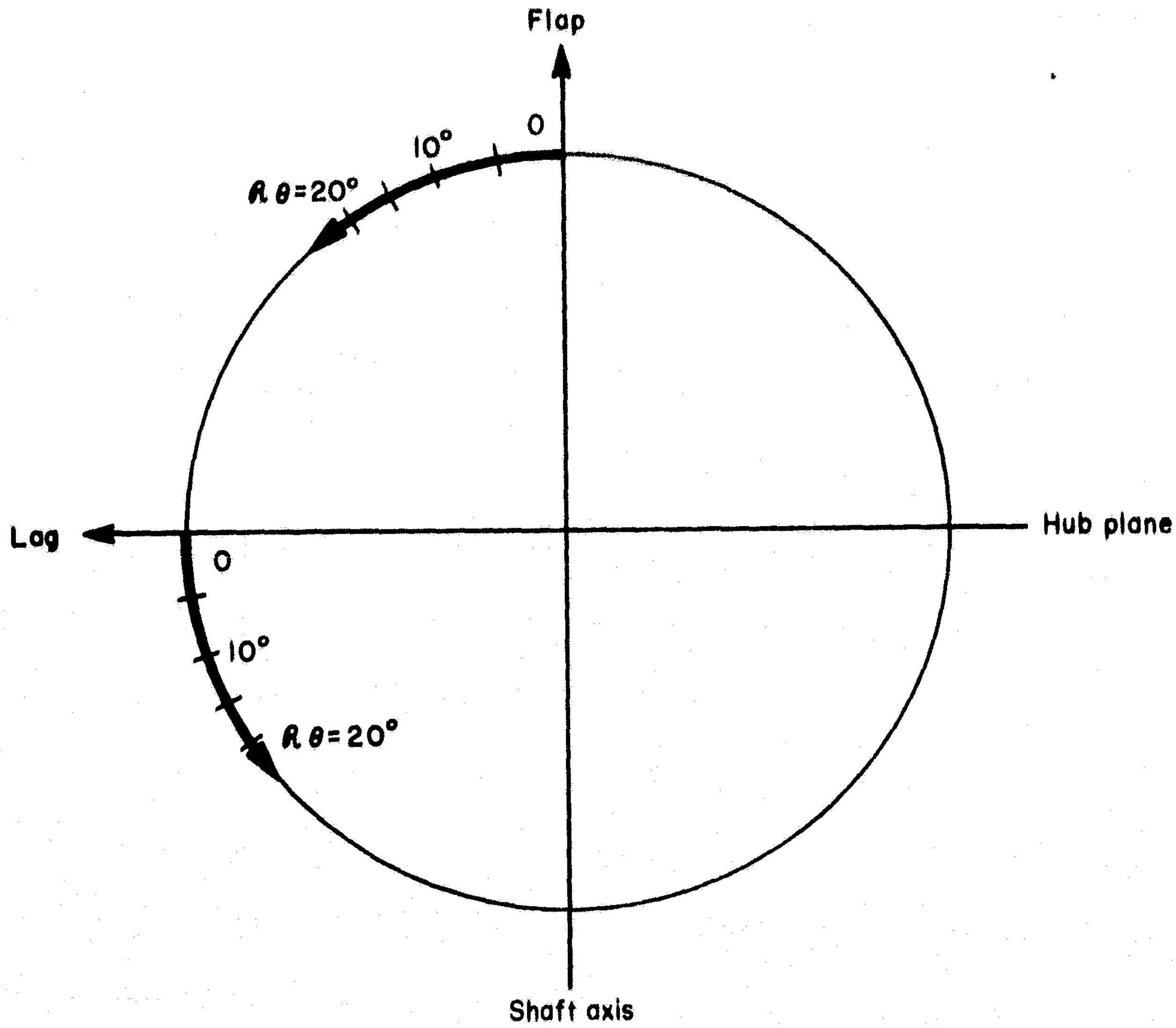
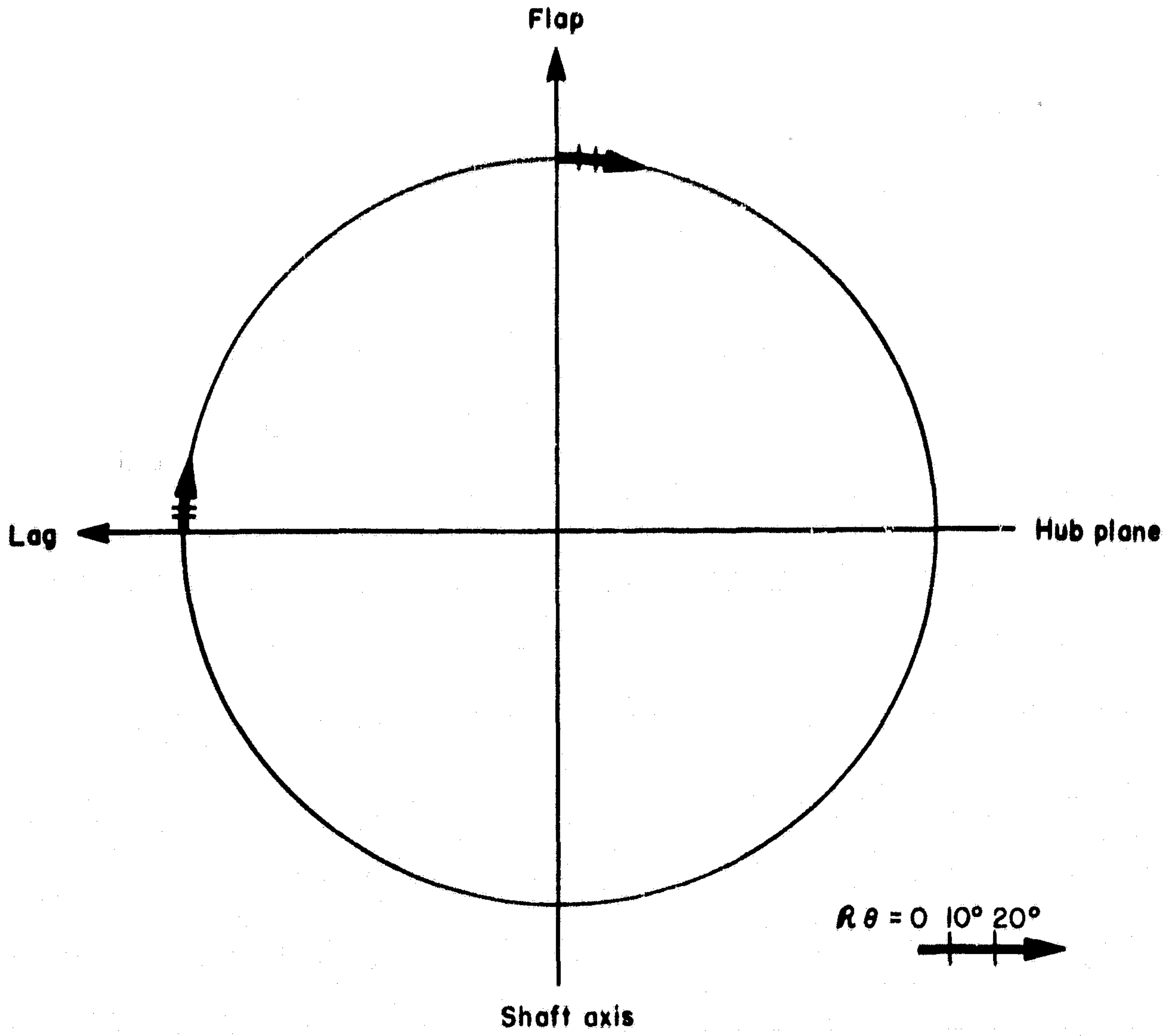


Figure 4 Blade bending natural frequencies for soft-inplane and stiff-inplane cases, as a function of the structural pitch angle $\beta\theta$.



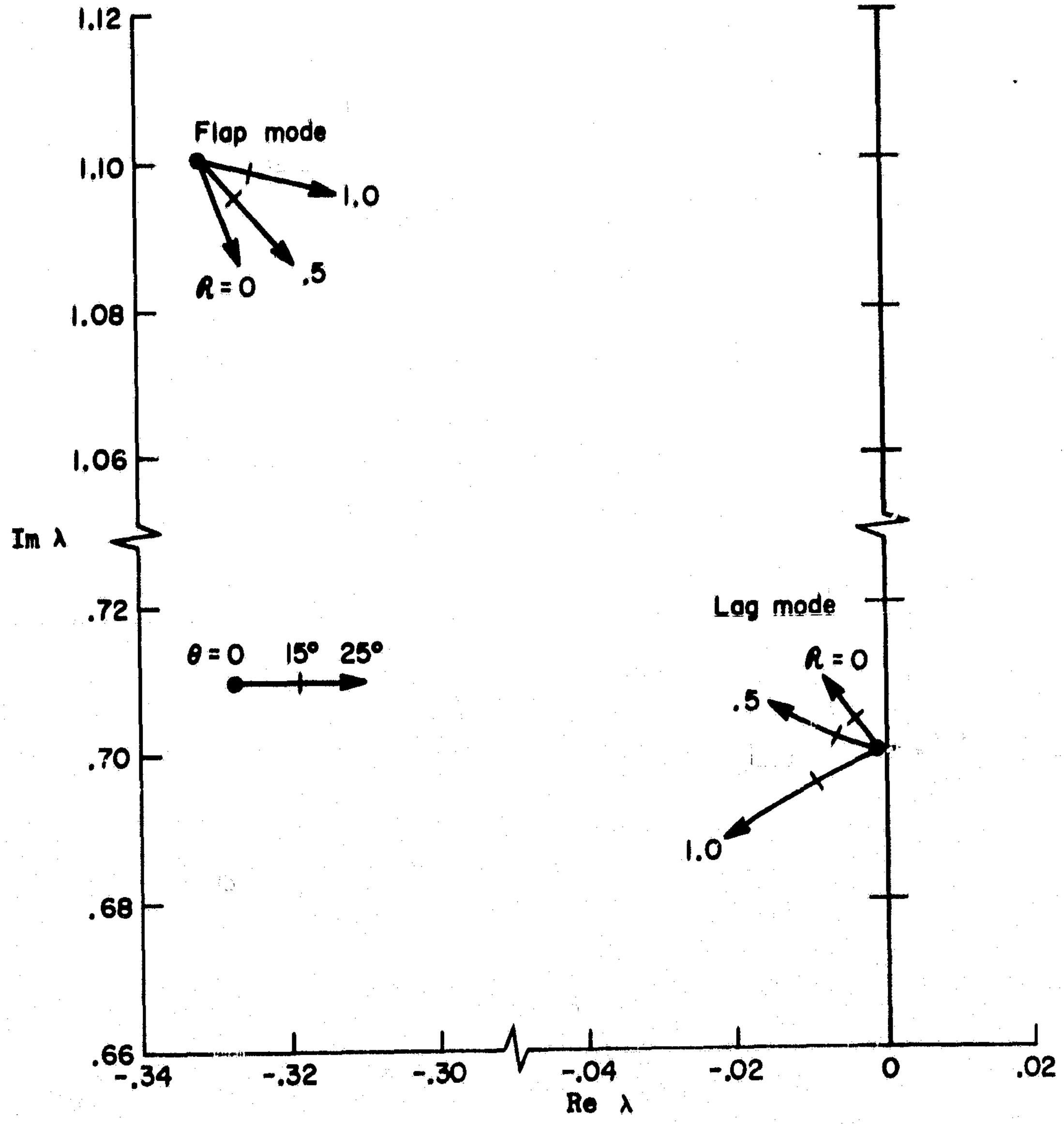
(a) Stiff-inplane rotor, $\nu_\beta = 1.15$ and $\nu_\zeta = 1.5$

Figure 5 Blade bending mode tip deflection as a function of the structural pitch angle $R\theta$.



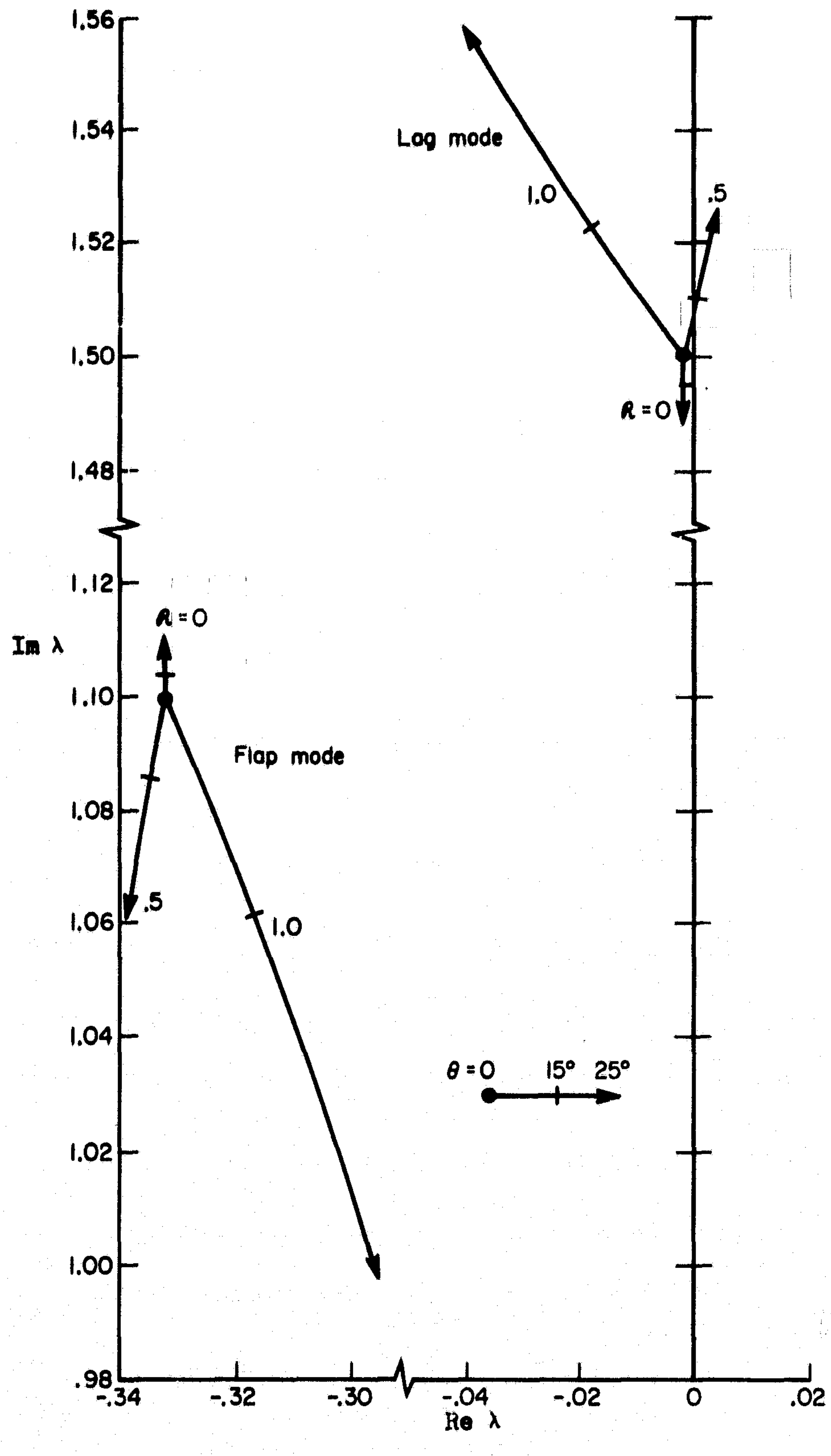
(b) Soft inplane rotor, $\nu_\beta = 1.15$ and $\nu_\zeta = 0.7$

<u>Figure 5</u> Concluded.



(a) Soft-inplane rotor, $\nu_\beta = 1.15$ and $\nu_\zeta = 0.7$

Figure 6 Root loci for a torsionally rigid blade ($\omega_\phi = \infty$, and no precone), with various values of structural coupling.



(b) Stiff-inplane rotor, ν_β = 1.15 and ν_ζ = 1.5

Figure 6 Concluded.

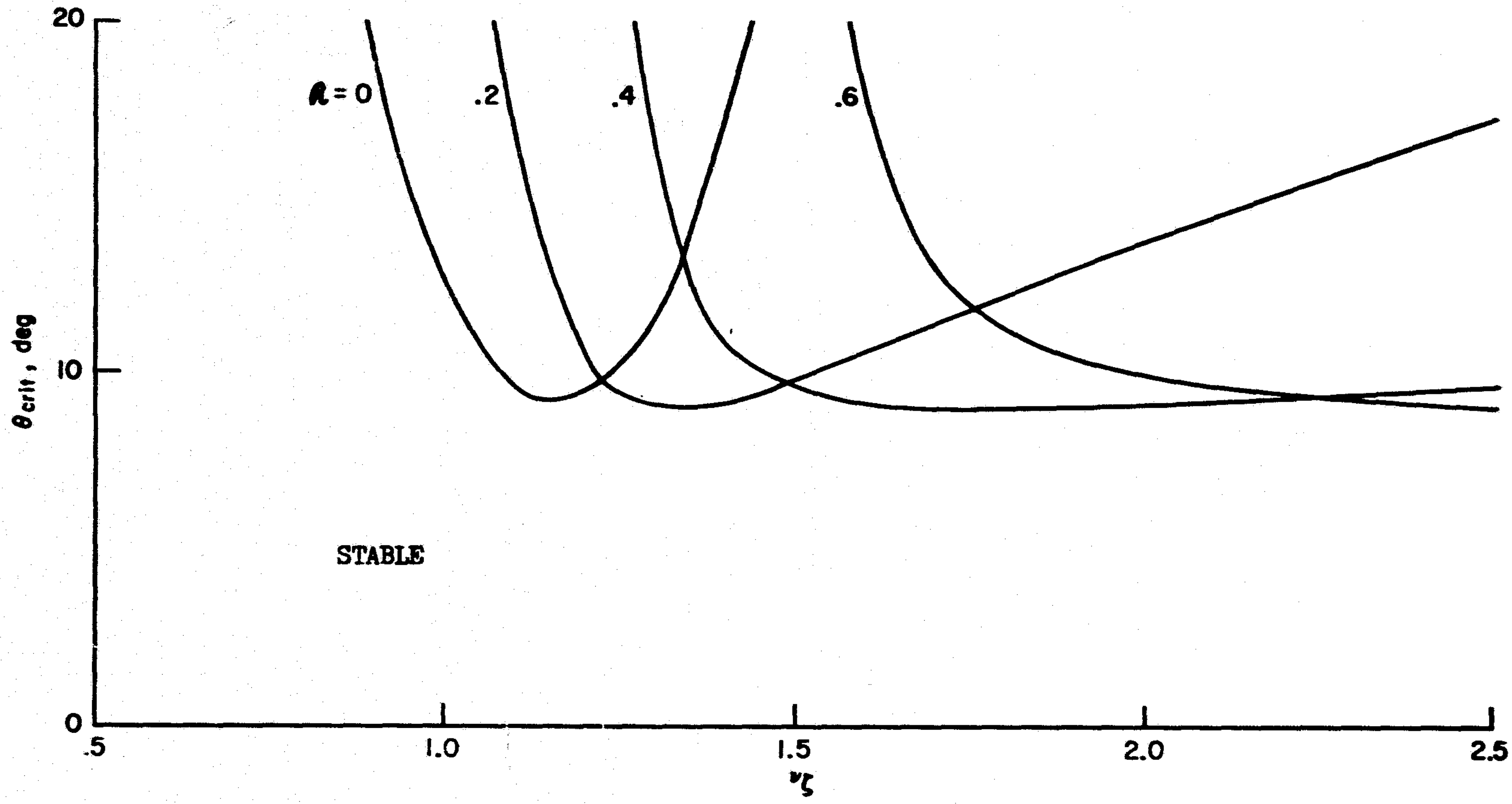


Figure 7 Stability boundaries for a torsionally rigid blade as a function of lag frequency ($\nu_\beta = 1.15$, $\omega_\phi = \infty$, and no precone), with various values of structural coupling.

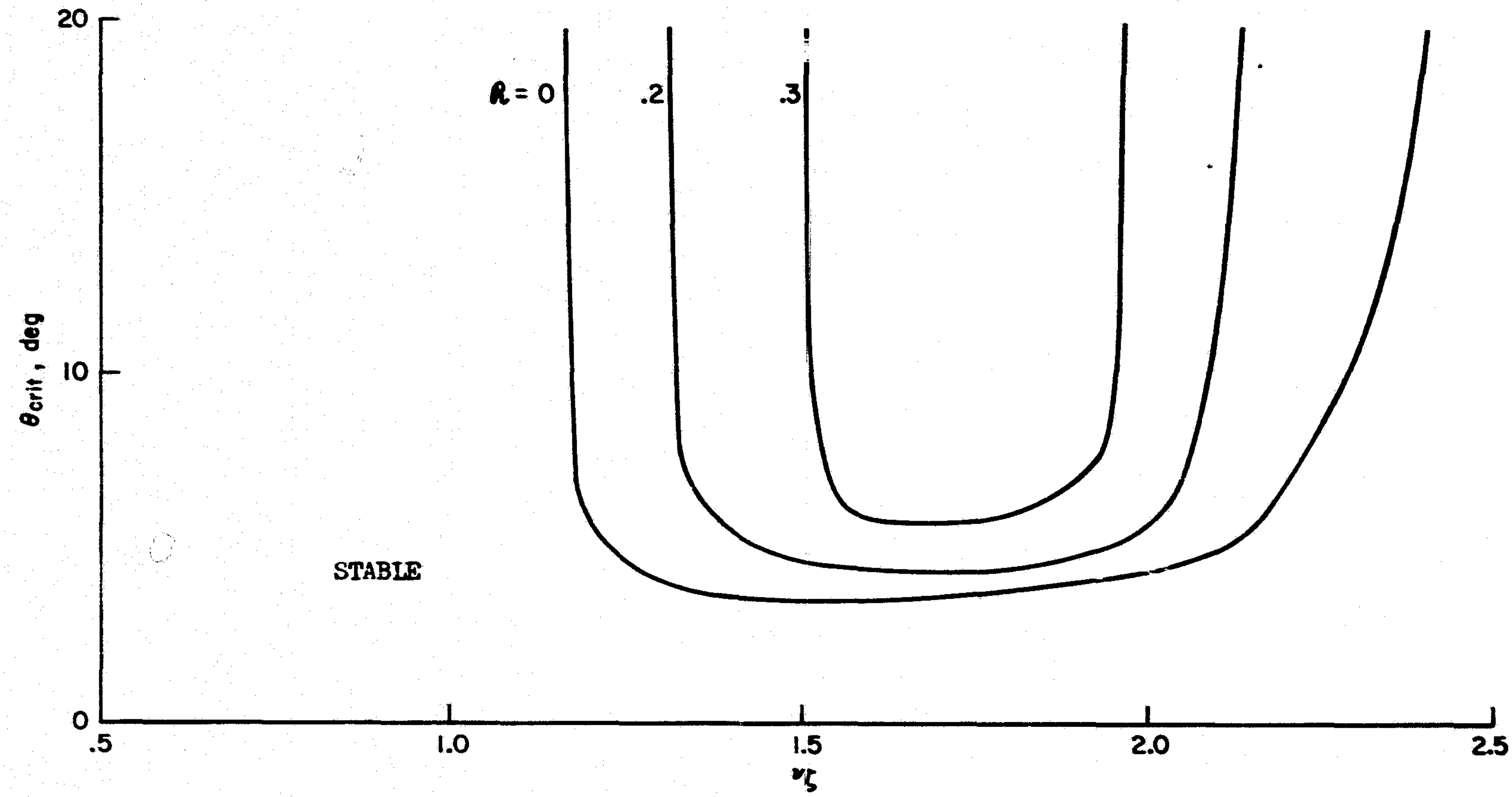


Figure 8 Stability boundaries for a blade with torsion frequency $\omega_\phi = 5$ as a function of lag frequency ($\nu_\beta = 1.15$, and no precone), with various values of structural coupling.

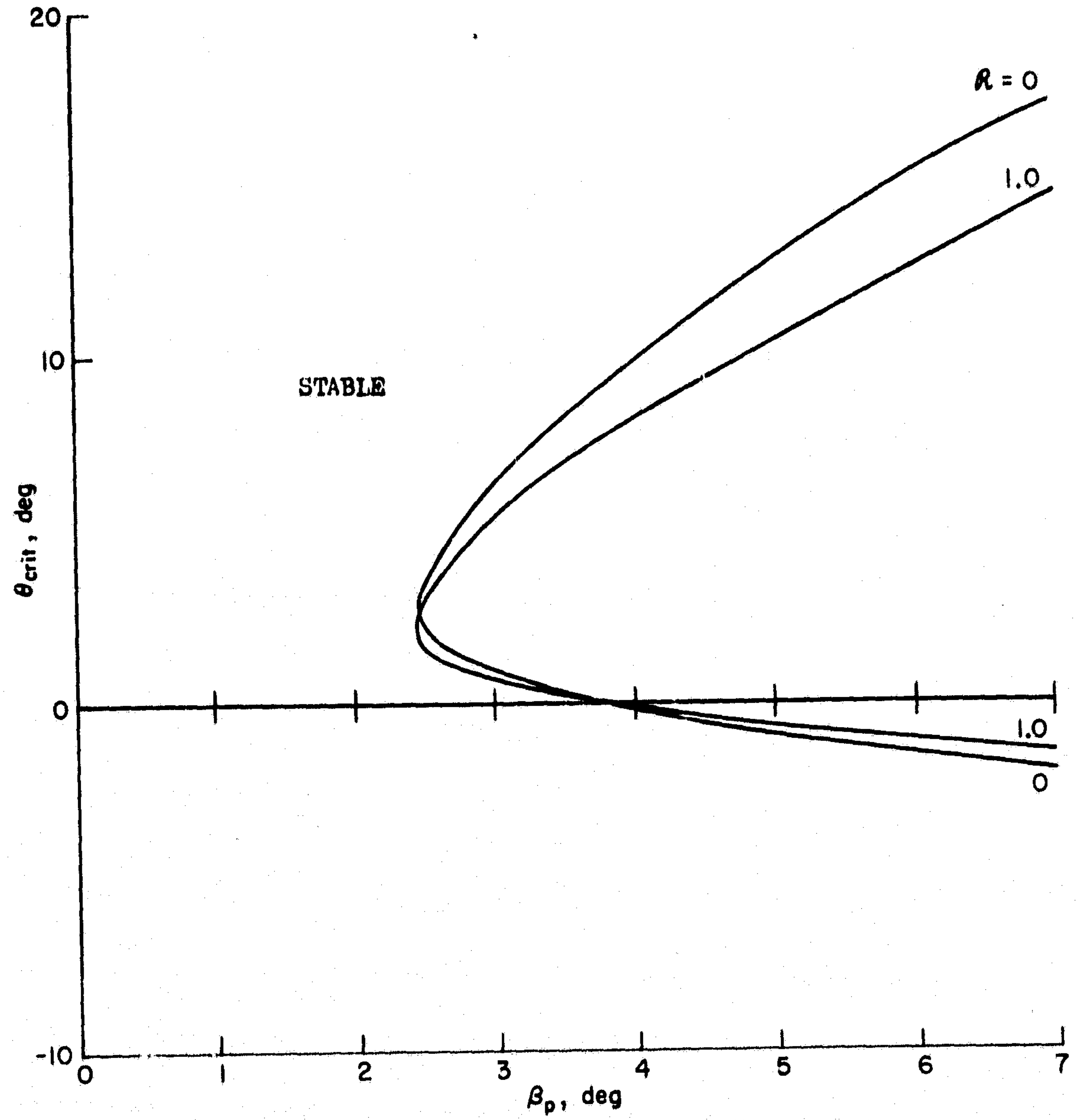


Figure 9 Stability boundaries as a function of precone angle β_p for a soft-inplane torsionally flexible blade (ν_β = 1.15, ν_ζ = 0.7, and ω_ϕ = 2.5), with various values of structural coupling.

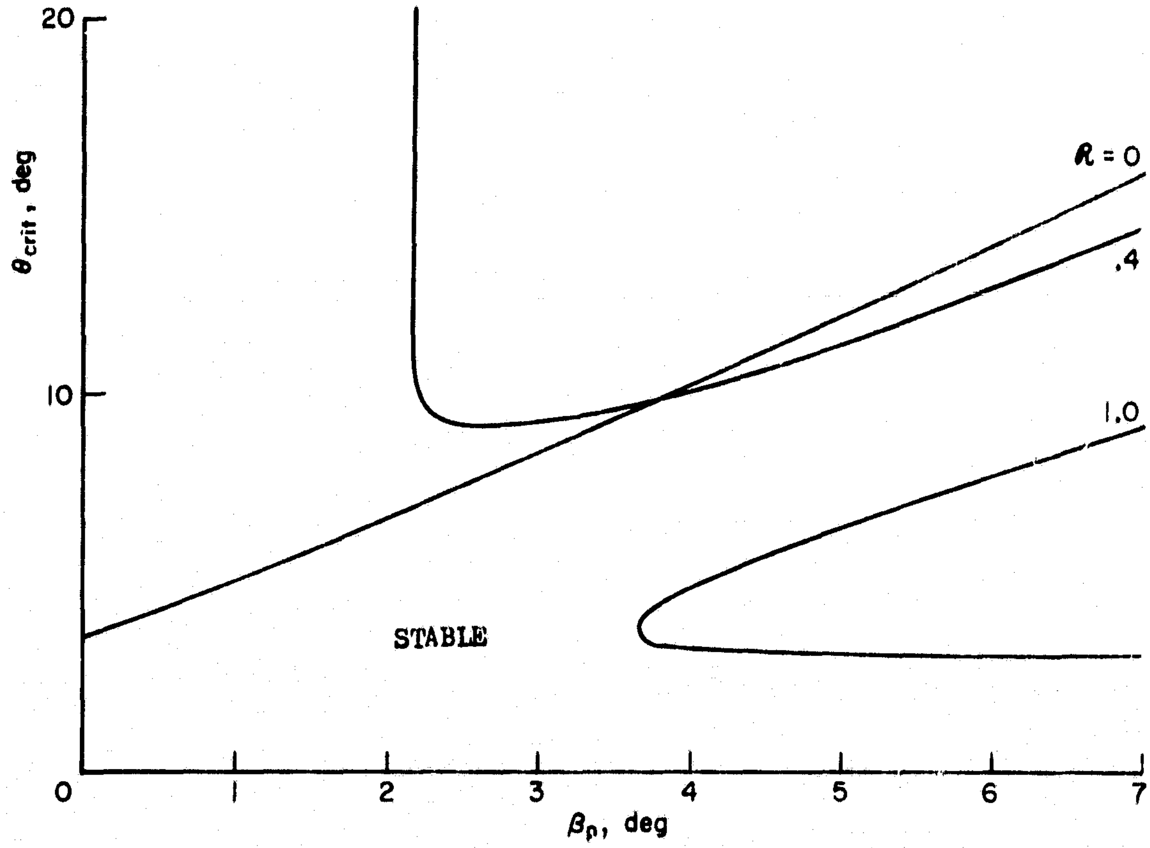


Figure 10 Stability boundaries as a function of precone angle β_p for a stiff-inplane torsionally flexible blade ($\nu_\beta = 1.15$, $\nu_\zeta = 1.5$, and $\omega_\phi = 5$), with various values of structural coupling.

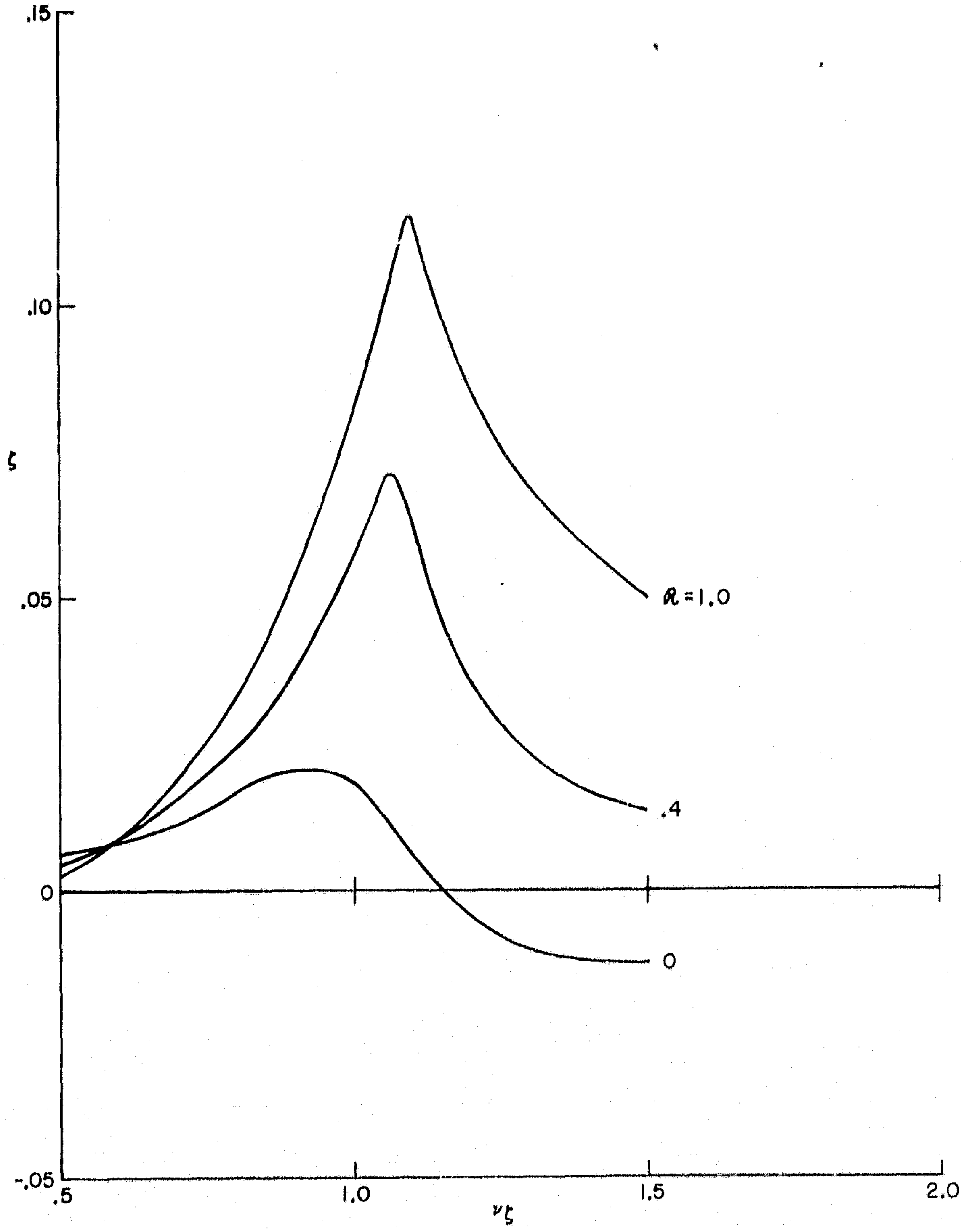


Figure 11 Lag mode damping ratio as a function of lag frequency ($\nu_\beta = 1.15$, $\omega_\phi = 5$, no precone, and collective pitch angle $\theta = 17.3^\circ$), with various values of structural coupling.